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A MODEL OF FRACTURE IN TRIPLEX UNDER SHOCK IMPACT

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The proposed method for calculation of the impact strength in triplex glass is used to demonstrate the possibility of a further improvement of the triplex structure based on complex thermal treatment of the glass.

One of the tests for triplex glass according to GOST 5727–88 is a blow inflicted with a sphere of weight $m = 2260 \pm 20$ g and diameter around 82 mm dropped from a height of 4 m. The sphere should not be able to penetrate into the glass for 5 sec after the impact.

The purpose of the present paper is analytical prediction of triplex properties under a shock effect and identification of the possibilities of further improvement of the structure of multilayer sheet glass subjected to complex heat treatment [1].

A model of the fracture of triplex glass has been developed, in which triplex is a multilayer product including two glass panes joined by adhesive polyvinyl butyral film (PVB film).

The standard triplex formula is 3 + 3, in which the figures indicate the glass thickness in millimeters, and the symbol "+" means the presence of the adhesive PVB layer, whose thickness is usually 0.76 mm.

This structure was taken as the reference standard, and all subsequent modifications and their results were given in relation to it.

The model is based on the energy balance of the consecutive destruction of the triplex layers:

$$E_0 = \sum_{i=1}^{3} \Delta E_i + E_{\text{res}}, \tag{1}$$

where E_0 is the kinetic energy of the sphere at the moment of its contact with the multiple glass surface; ΔE_i is the potential energy absorbed by each layer; E_{res} is the residual energy in the case of a complete breakthrough of multiple glass by the sphere without stopping; according to GOST 5727–88, $E_{\text{res}} = 0$.

The known values are the left-hand side of balance (1) $E_0 = mgH$ ($m = 2.26$ kg, $g = 9.81$ m/sec^2, $H = 4$ m) and the speed of co-impact of the sphere and the surface $v_0 = \sqrt{2gH}$. For the given testing conditions, $v_0 = 8.859$ m/sec.

Special attention is paid to the loss of kinetic energy in the fracture of the first layer; here

$$\Delta E_1 = E_{\text{el.s}} + E_{\text{b}} + E_{\text{el.g}}^{(1)} + E_{\text{f}}^{(1)}, \tag{2}$$

where $E_{\text{el.s}}$ is the energy of elastic deformation of the sphere, E_{b} is the energy of elastic bending of the whole multiple glass, $E_{\text{el.g}}^{(1)}$ is the energy of elastic deformation of the first layer of glass, and $E_{\text{f}}^{(1)}$ is the energy of fracture of the first layer.

Once the right-hand components of balance (2) are determined, the velocity of the sphere after the breakthrough of the first layer is

$$v_1 = \sqrt{v_0^2 - \frac{2}{m}\Delta E_1}\,.$$

After that, the sphere with the initial velocity v_1 interacts with the plastic PVB film layer and loses part of its energy ΔE_2 on its deceleration in this layer. The sphere velocity after the breakthrough of the second layer will be

$$v_2 = \sqrt{v_1^2 - \frac{2}{m}\Delta E_2}\,.$$

Finally, in fracturing the third layer, the energy loss is

$$\Delta E_3 = E_{\text{el.g}}^{(3)} + E_{\text{f}}^{(3)},$$

and the velocity is

$$v_3 = \sqrt{v_2^2 - \frac{2}{m}\Delta E_3}\,.$$

The requirement of the standard ($v_3 = 0$) makes it possible to represent the specified balance in the closed form in the control variant of analytical calculations.

The components of balance (2) were determined based on the conditions of indentation of the sphere into the glass surface, in accordance with the fundamental relationships of

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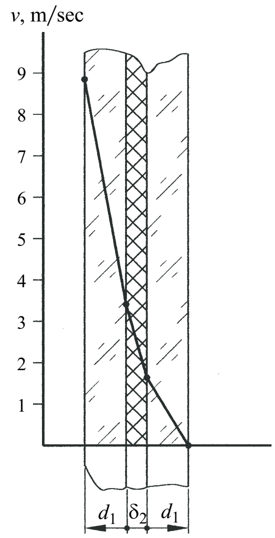

Fig. 1. Variations in the velocity of the sphere in testing the reference variant of triplex.

G. Hertz [2], which, after certain transformations, were reduced to the following relationships:

$$\left.\begin{aligned} E_{\mathrm{el.s}} &= 2.16\frac{\sigma_{\mathrm{el}}^2}{E_{\mathrm{s}}}R^3; \\ E_{\mathrm{el.g}}^{(1)} &= 3.759\frac{\sigma_{\mathrm{el}}^2}{E_{\mathrm{c}}}R^2 d_1; \\ E_{\mathrm{f}}^{(1)} &= 3.759\frac{\sigma_{\mathrm{s}}}{E_{\mathrm{g}}}R^2 d_1, \end{aligned}\right\} \tag{3}$$

and the potential bending energy was determined earlier [3] and amounted to

$$E_{\mathrm{b}} = \frac{mv_0^2}{2}\frac{1}{1+\frac{1}{2}\frac{m_{\mathrm{pl}}}{m}},$$

where σ_{el} and σ_{s} are the limit of elasticity and the ultimate strength of glass (in the first approximation $\sigma_{\mathrm{el}} = \sigma_{\mathrm{s}}$); E_{s} and E_{g} are the values of the Young's modulus of the materials of the sphere and glass, respectively; R is the sphere radius; d_1 is the glass thickness; m_{pl} is the weight of the tested plate limited by the conditions of the article resting on a support, according to GOST 5727–88.

Relationships (3) are maintained for the third layer (with the respective alteration of indices)

The plastic layer (PVB film) behaves in a different way. The loss of energy in its fracture is determined by the hydrodynamic resistance of this layer, or by deceleration in this layer:

$$\Delta E_2 = E_{\mathrm{r}} = C\rho A\frac{v_1^2\delta}{2},$$

where C is a constant, ρ is the density of the film material, A is the cross-section area of the sphere, and δ is the film thickness.

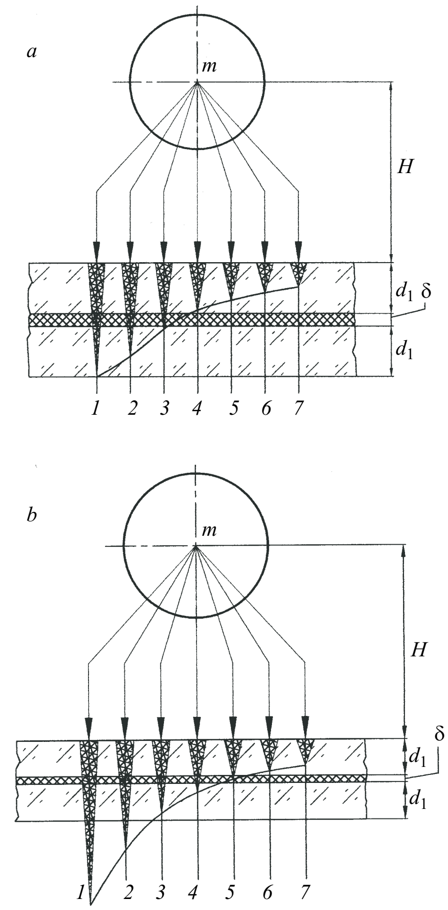

Fig. 2. The effect of surface stress on the breakthrough depth in the reference variant of triplex (*a*) and in thin triplex (*b*): *1*, *2*, *3*, *4*, *5*, *6*, and *7*) σ_{c} = 0, 20, 40, 60, 80, 100, and 120 MPa, respectively.

The proposed method was used in the control calculation of the reference variant of triplex 3 + 3 with the following initial data: $\sigma_{\mathrm{el}} = \sigma_{\mathrm{s}} = 75$ MPa, $R = 41$ mm, $E_{\mathrm{s}} = 2 \times 10^5$ MPa, $d_1 = 3$ mm, $m_{\mathrm{pl}} = 1.35$ kg, $\rho = 1100$ kg/m^3, $\delta_2 = 0.76$ mm, and $C = 233.82$.

The purpose of the control calculation was to find out the variations in the velocity of the sphere in the depth of the product under the specified testing conditions (Fig. 1). It can be seen that the most significant decrease in the sphere velocity (from 8.859 to 3.415 m/sec) occurs in the first layer, which directly absorbs the impact. A further decrease in the velocity due to the deceleration of the sphere in the plastic layer gives the value $v_2 = 1.644$ m/sec, with subsequent damping to $v_3 = 0$, which correlates with hovering of the sphere prescribed by the standard.

The triplex structure can be upgraded via a complex thermal treatment of glass with induced compressive surface stress σ_{c} of a preset value. The strength of a single glass pane in this case is determined by the sum of the values of the strength of the initial (annealed) glass and the surface compressive stress:

$$\sigma_{\mathrm{s}}^* = \sigma_{\mathrm{s}} + \sigma_{\mathrm{c}}.$$

In accordance with the above method, the depth of penetration of a falling sphere was calculated for different values of σ_c. The variation limits for compressive surface stress ranged from 10 to 120 MPa, and the calculation results are represented in a diagram (Fig. 2). A significant decrease in the breakthrough depth was observed with increasing σ_c, which leads to the assumption that the triplex thickness can be radically altered while preserving its strength properties.

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